A Review of Reflectance Nomenclature Used in Remote Sensing

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Abstract

Field and laboratory radiometers have long been used to characterize homogeneous surface targets for their multiangle reflectance properties. Within the last few years space-based multiangle imaging spectroradiometers have been deployed, including the Along-Track Scanning Radiometer-2 (ATSR), the Polarization and Directionality of the Earth's Reflectances (POLDER) instrument, and the Multiangle Imaging SpectroRadiometer (MISR). Other scanning instruments, such as the Moderate Resolution Imaging Spectrometer (MODIS) make use of successive passes to make multiangle observations. The synergistic approach of global monitoring from space, combined with localized detailed observations from the field, will allow greater exploitation of these multiangle data. As this science advances, results will likewise require additional preciseness of terminology in order to differentiate between parameters which may be reported in a variety of spectral and field-of-view integrations, as well as inherent versus observed properties. This paper reviews the reflectance terminology that is used by the remote sensing community.

1. Introduction

The angular reflectance pattern of clouds, aerosol layers, vegetation canopies, soils, and snow and ice fields are now being measured by the remote sensing community. Application of these data include studies of the Earth's radiation balance, climate, and land use change. Of particular interest is the impact of varying cloud, aerosol, and surface cover type on the distribution of radiation within the atmosphere/surface system. Multiangle data is important in this regard since it allows another dimension of information to be exploited in the process of decoupling surface radiative effects from atmospheric effects.

The ability to obtain multiangle data on a global basis has only been available within the last decade, starting with the Along-Track Scanning Radiometer (ATSR) launched in 1991 on ERS-1. The most recent instruments include the ATSR-2 [Stricker et al., 1995] on ERS-2, the Polarization and Directionality of the Earth's Reflectances (POLDER) instrument [Deschamps et al., 1994] on ADEOS (operational from November 1996 to June 1997), and the Multiangle Imaging SpectroRadiometer (MISR) [Diner, et al., 1998] on EOS Terra. The Moderate Resolution Imaging Spectrometer (MODIS) [Barnes, et al., 1998], also on EOS Terra, is a traditional cross-track

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scanning radiometer but makes use of successive passes of a given target to create multiangle datasets. Along with the increased capability of making multiangle observations from space was a corresponding advancement in multiangle field observation methodologies and instrumentation. In order to intercompare these different types of data sets, it is important to discern the difference between inherent parameters from the observed radiance, narrowband from broadband, and differential from that integrated over a solid angle or hemisphere.

Because of the breadth and advances in multiangle studies, it is not a surprise that different working groups have developed slight variants to the reflectance nomenclature, as originally proposed by Nicodemus *et al.* [1977]. This paper reviews current reflectance terminology, as modified to meet the needs of a new generation of instruments and methodologies. The terminology presented here serves this goal, and is applicable to a wide range of spatial scales of the measurement footprint, extending from multiple kilometer in size surface areas down to meter-sized and smaller. It is routinely used in measurement analysis procedures for both continuous spacecraft data streams and data acquired during field measurement campaigns.

The directional reflective properties of a surface is mathematically described by a bidirectional reflectance distribution function (BRDF). The term "bidirectional" implies single directions for the incident and reflected radiances (emanating from and entering differential solid angles, respectively). However, if the directional reflective properties are actually measured or retrieved, then a more convenient description is the bidirectional reflectance factor (BRF), more fully described in the next section. Bidirectional conditions can be approximately achieved in the field or from space if the wavelength of the illumination implies negligible Rayleigh scattering (i.e., direct sunlight only) and if the measuring instrument has a very small field-of-view. In practice, however, remote sensing measurements of surface reflectance usually are contaminated by atmospheric effects. Direct sunlight plus a diffuse component due to atmospheric scattering creates an illumination field which is hemispherical in angular extent. Reflectance data that are uncorrected for this atmospheric effect are reported as a hemispherical-directional reflectance factor (HDRF) [Standard nomenclature dictates that the angular characteristics of the illumination is mentioned first, followed by the angular characteristics of the reflected radiance. Thus, e.g., hemispherical-directional... implies a hemispherically integrated illumination and a reflected radiance in a single direction. On the other hand, directional-hemispherical... implies that the illumination is single directional and the reflected radiance is integrated over the hemisphere.]

Oftentimes the reflectance quantity of interest is not that directed into a small solid angle, but rather the total energy reflected or scattered from a surface. Parameters such as directional-hemispherical reflectance (DHR) describe such a reflectance, and is also an inherent property of the surface, independent of atmospheric conditions. Atmospheric-dependent descriptors include the bihemispherical reflectance (BHR) and the spectrally integrated BHR known simply as the albedo. These parameters are described in further detail in the sections below.

2. Reflectance Nomenclature

Thus far, the term "reflectance" has been used loosely to refer to the relative amount of scattering by a surface. However, it is important to define the specific measures of radiation flux that will be provided by space-based instruments or that will be observed in a field measurement program. Figure 1 provides some simple sketches that illustrate some of the following radiometric quantities.

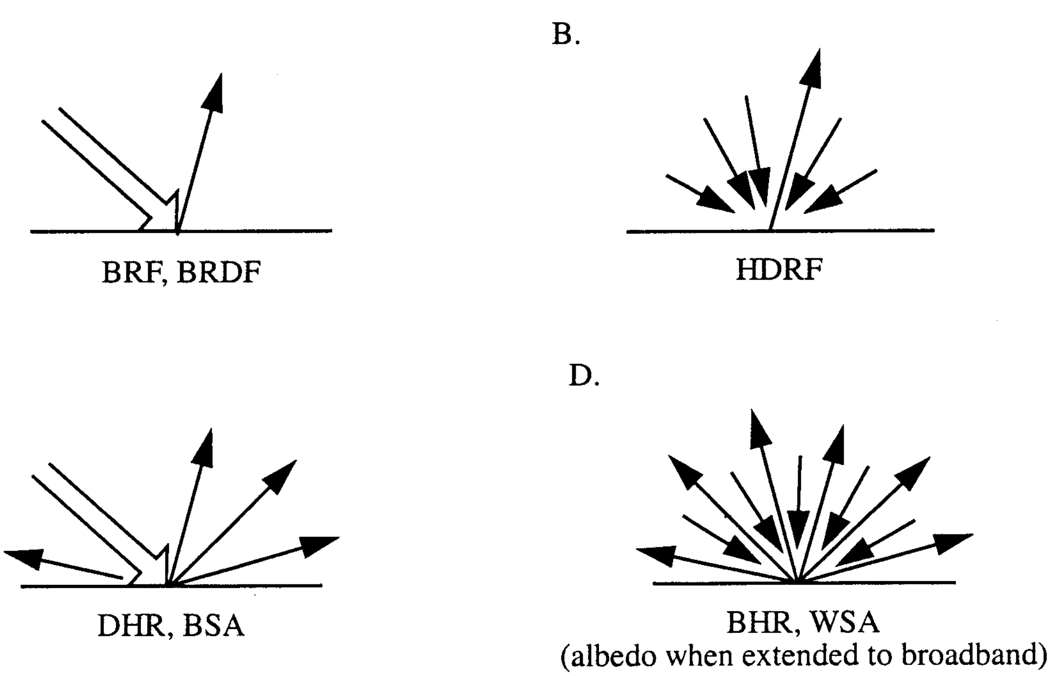

Figure 1. Reflectance nomenclature summary. The broad arrow represents an irradiance from a plane-parallel source. All other arrows represent incident and reflected radiance fields.

2.1. Single Directional Illumination

2.1.1. Bidirectional Reflectance Distribution Function (BRDF)

The surface bidirectional reflectance distribution function (BRDF) f_r describes the scattering of a parallel beam of incident light from one direction in the hemisphere into another direction in the hemisphere (Figure 1A). Ignoring any spectral dependence of the BRDF, we may write

$$f_r(\theta_i, \phi_i; \theta_v, \phi_v) = \frac{dL_v(\theta_i, \phi_i; \theta_v, \phi_v)}{dE_i(\theta_i, \phi_i)} \quad (\mathrm{ster}^{-1}) \qquad (1)$$

where $\theta_i, \phi_i; \theta_v, \phi_v$ are the zenith and azimuth angles of the direction of illumination and reflection, respectively; dE_i is the irradiance from the illumination direction; and dL_v is the radiance reflected into the differential solid angle at θ_v, ϕ_v [Nicodemus *et al.*, 1977]. The irradiance can be expressed as

$$dE_i(\theta_i, \phi_i) = \cos\theta_i \sin\theta_i L_i(\theta_i, \phi_i) d\theta_i d\phi_i \tag{2}$$

where L_i is the illuminating radiance from a differential solid angle at θ_i, ϕ_i. Since both dL_v and dE_i are defined in terms of differential solid angles, in theory f_r cannot be directly measured. In practice, however, the BRDF is assumed to be retrievable from radiance measurements made over a small solid angle and using a plane parallel light source (e.g. laser or sun). Also, the BRDF is usually assumed to be symmetric about the principle plane of irradiance; that is, to be a function of θ_i, θ_v, ϕ, where the relative azimuth angle $\phi = |\phi_v - \phi_i|$.

2.1.2. Bidirectional Reflectance Factor (BRF)

The bidirectional reflectance-distribution factor (BRF) R is defined as the ratio of the reflected flux $d\Phi_v$ from the target surface area dS in a particular direction to the reflected flux $d\Phi_v^{lam}$ from a white (i.e., non-absorbing and non-transmitting) Lambertian surface of same area dS and under the same conditions of reflection and illumination as $d\Phi_v$. For the single direction illumination condition expressed by Eq. (2), the BRF can be written as

$$\begin{aligned}
R(\theta_i, \phi_i; \theta_v, \phi_v) = \frac{d\Phi_v(\theta_i, \phi_i; \theta_v, \phi_v)}{d\Phi_v^{lam}(\theta_i, \phi_i)} &= \frac{\cos\theta_v \sin\theta_v dL_v(\theta_i, \phi_i; \theta_v, \phi_v) d\theta_v d\phi_v d\phi_v dS}{\cos\theta_v \sin\theta_v dL_v^{lam}(\theta_i, \phi_i) d\theta_v d\phi_v dS} \\
&= \frac{dE_i(\theta_i, \phi_i)}{dL_v^{lam}(\theta_i, \phi_i)} \cdot \frac{dL_v(\theta_i, \phi_i; \theta_v, \phi_v)}{dE_i(\theta_i, \phi_i)} \\
&= \frac{f_r(\theta_i, \phi_i; \theta_v, \phi_v)}{f_r^{lam}(\theta_i, \phi_i)} \\
&= \pi \cdot f_r(\theta_i, \phi_i; \theta_v, \phi_v)
\end{aligned} \tag{3}$$

where dL_v^{lam} is dependent only on the direction of illumination θ_i, ϕ_i. Note that the BRDF for a Lambertian surface is $1/\pi$ and that the BRF therefore is proportional to the BRDF. Since the BRF is a ratio of two fluxes, however, it is a unitless quantity, unlike the BRDF.

When the bidirectional reflectance properties of a surface are measured, the measurement procedure usually follows the definition of the BRF. The measurements of the fluxes reflected from the target surface and the Lambertian surface are made with the same instrument and the ratioing procedure tends to cancel much of the uncertainty in the absolute radiometric calibration of the measuring instrument. A Spectralon panel serves as an excellent approximation to a Lambertian surface and can be used in both laboratory and field work. If the surface of interest is the top-of-atmosphere (TOA), then its BRF is determined using the measured value of reflected flux $\Delta\Phi^{\mathrm{TOA}}$ obtained by the space-based instrument for a given area ΔS and a computed value for the Lambertian surface reflected flux. Thus, the TOA BRF can be expressed as

$$R_{\mathrm{TOA}}(\theta_0, \phi_0;\theta_v, \phi_v) = \frac{d\Phi_{\mathrm{v}}^{\mathrm{TOA}}(\theta_0, \phi_0;\theta_v, \phi_v)}{d\Phi_{\mathrm{v}}^{\mathrm{lam,\,TOA}}(\theta_0, \phi_0)} \cong \frac{\Delta\Phi^{\mathrm{TOA}}(\theta_0, \phi_0;\theta_v, \phi_v)}{\cos\theta_0 E_0 \Delta S} \tag{4}$$

where θ_0 and ϕ_0 are the solar zenith and azimuth angles, respectively, at the TOA and E_0 is the TOA normal solar irradiance. If the BRF of the Earth's surface is to be determined using $\Delta\Phi^{\mathrm{TOA}}$, then all effects of the intervening atmosphere (scattering and absorption) must be removed from the measurements [e.g., Martonchik *et al.*, 1998].

2.2. Hemispherical illumination

2.2.1. Hemispherical–Directional Reflectance Factor (HDRF)

The HDRF is identical in definition to the BRF except that the illumination direction is not single directional but hemispherical. If the illumination is hemispherical, then a surface receives radiance from all directions in the hemisphere and that the radiance is not necessarily constant from all directions (Figure 1B). Under typical field conditions the surface incident radiance field is considered hemispherical, consisting of a mixture of solar (single directional or direct) and non-isotropic diffuse sky illumination. The HDRF R^{hem} can then be written as

$$\begin{aligned} R^{\mathrm{hem}}(\theta_v, \phi_v) &= \frac{d\Phi_{\mathrm{v}}(\theta_v, \phi_v)}{d\Phi_{\mathrm{v}}^{\mathrm{lam}}} = \frac{\cos\theta_v \sin\theta_v L_{\mathrm{v}}(\theta_v, \phi_v) d\theta_v d\phi_v dS}{\cos\theta_v \sin\theta_v L_{\mathrm{v}}^{\mathrm{lam}} d\theta_v d\phi_v dS} \\ &= \frac{L_{\mathrm{v}}(\theta_v, \phi_v)}{L_{\mathrm{v}}^{\mathrm{lam}}} = \frac{\int_{2\pi} f_{\mathrm{r}}(\theta_{\mathrm{i}}, \phi_{\mathrm{i}};\theta_v, \phi_v) d\Phi_{\mathrm{i}}(\theta_{\mathrm{i}}, \phi_{\mathrm{i}})}{\int_{2\pi} \frac{1}{\pi} d\Phi_{\mathrm{i}}(\theta_{\mathrm{i}}, \phi_{\mathrm{i}})} \\ &= \frac{\int_{2\pi} f_{\mathrm{r}}(\theta_{\mathrm{i}}, \phi_{\mathrm{i}};\theta_v, \phi_v) \cos\theta_{\mathrm{i}} \sin\theta_{\mathrm{i}} L_{\mathrm{i}}(\theta_{\mathrm{i}}, \phi_{\mathrm{i}}) d\theta_{\mathrm{i}} d\phi_{\mathrm{i}}}{\frac{1}{\pi}\int_{2\pi} \cos\theta_{\mathrm{i}} \sin\theta_{\mathrm{i}} L_{\mathrm{i}}(\theta_{\mathrm{i}}, \phi_{\mathrm{i}}) d\theta_{\mathrm{i}} d\phi_{\mathrm{i}}} \end{aligned} \quad , \tag{5}$$

where use was made of Eqs. (1) and (2). Unlike the BRF, which is a function only of the intrinsic scattering properties of the surface, the HDRF depends both on surface scattering properties and on the angular distribution of the illumination. This distribution is governed mainly by scattering within the atmosphere but will also include some dependence on the surface directional reflectance itself since there will be multiple reflections of the radiance between the atmosphere and surface. Note that the HDRF provides a convenient, unitless representation of the reflected radiance. From Eq. (5) it can be seen that L_v is directly proportional to the HDRF R^{hem}, with the constant of proportionality being the surface incident flux divided by π

The HDRF is the easiest and the most basic measurement made of directional surface reflectance in field work but it usually takes some effort to determine or retrieve from the HDRF measurement, the corresponding BRDF f_r (or, equivalently, the BRF), the more fundamental surface reflectance function. This retrieval process is known as an "atmospheric correction". To adequately perform such a correction, additional field measurements to characterize the atmospheric state must also be made, simultaneous with the HDRF measurements.

If the surface HDRF is not measured at the surface but is to be determined using space-based measurements, $\Delta\Phi^{TOA}$, then the atmospheric correction process to retrieve the BRF (see section **2.1.2**) provides the HDRF as an intermediate product [Martonchik *et al.*, 1998].

2.3. Hemispherical Reflectances

2.3.1. Albedo

The term albedo comes from climatology. The AMS Glossary of Weather and Climate (1997) defines albedo as,

"... the ratio of the amount of electromagnetic radiation reflected by a body to the amount incident upon it; commonly expressed as a percentage. Usually, albedo refers to radiation in the visible range or to the full spectrum of solar radiation...."

Albedo is a function of both atmosphere and surface. Given a fixed surface BRF, albedo will change if the angular distribution of beam and sky radiance changes. Thus, the albedo will depend on both solar zenith angle and atmospheric state. In addition, multiple scattering between surface and atmosphere will change the angular distribution of sky radiance if the atmosphere remains constant but the surface BRF changes. Therefore, albedo is not a true surface property, but rather a function of solar beam direction, atmospheric state, and surface BRF.

Albedo can be measured at both the top-of-atmosphere and surface. From a planetary perspective, TOA albedo for the earth as a whole is a key parameter in the global energy balance. However, for modeling the transport of energy, matter, and momentum between the surface and lower atmosphere, surface albedo is a primary forcing variable that needs to be spatially distributed.

Albedo can be measured in the field using an albedometer, which consists of paired pyranometers looking upward and downward. The ratio of upwelling to downwelling radiant flux, measured over the whole hemisphere, is the albedo. Typically the pyranometers measure the full solar shortwave spectrum; however, albedometers may be filtered to eliminate shorter wavelengths, so that a separation, e.g. into visible (0.3–0.7 μm) and near-infrared to shortwave-infrared bands (0.7–5.0 μm) can be obtained from paired albedometers.

2.3.2. Directional–Hemispherical Reflectance (DHR)

One form of albedo, the DHR, is the case of illumination from a plane parallel beam. Thus, the DHR A_{DHR} is the ratio of the flux $d\Phi_{\mathrm{v}}$ for light reflected by a surface area dS into a hemisphere to the illumination flux $d\Phi_{\mathrm{i}}$, when the target is illuminated with a narrow cone of light from direction θ_i, (Figure 1C). It is written as

$$A_{\mathrm{DHR}}(\theta_i, \phi_i) = \frac{d\Phi_{\mathrm{v}}(\theta_i, \phi_i)}{d\Phi_{\mathrm{i}}(\theta_i, \phi_i)} = \frac{dS\int_{2\pi} dL_{\mathrm{v}}(\theta_i, \phi_i;\theta_v, \phi_v)\cos\theta_v\sin\theta_v d\theta_v d\phi_v}{d\Phi_{\mathrm{i}}(\theta_i, \phi_i)}$$

$$= \frac{d\Phi_{\mathrm{i}}(\theta_i, \phi_i)\int_{2\pi} f_{\mathrm{r}}(\theta_i, \phi_i;\theta_v, \phi_v)\cos\theta_v\sin\theta_v d\theta_v d\phi_v}{d\Phi_{\mathrm{i}}(\theta_i, \phi_i)}$$

$$= \int_{2\pi} f_{\mathrm{r}}(\theta_i, \phi_i;\theta_v, \phi_v)\cos\theta_v\sin\theta_v d\theta_v d\phi_v \quad , \qquad (6)$$

with a substitution using Eq. (1) and the relation $d\Phi_{\mathrm{i}} = dE_{\mathrm{i}}dS$

. The DHR is also referred to as “black-sky albedo” (BSA). It is the albedo that would be expected for beam irradiance only, with no diffuse radiation — thus the “black sky” designation. Since the DHR (or BSA) only depends on the BRDF, it is a true surface property and is independent of the atmosphere. It typically cannot be measured in the field since any field measurement will include illumination from diffuse skylight (see BHR below); however, like the HDRF, it can be derived or retrieved from such a measurement by accounting for the atmospheric effects.

2.3.3. Bihemispherical Reflectance (BHR)

The BHR A_{BHR} is the ratio of the flux Φ_{v} of light reflected from surface area dS into a hemisphere to the incident flux Φ_{i}, when the area is illuminated by an arbitrary radiation field, L_{i}, hemispherical in angular extent (Figure 1D). Thus,

$$A_{BHR} = \frac{\Phi_v}{\Phi_i} = \frac{dS\int_{2\pi} L_v(\theta_v, \phi_v)\cos\theta_v \sin\theta_v d\theta_v d\phi_v}{dS\int_{2\pi} L_i(\theta_i, \phi_i)\cos\theta_i \sin\theta_i d\theta_i d\phi_i}$$

$$= \frac{\int_{2\pi}\int_{2\pi} f_r(\theta_i, \phi_i;\theta_v, \phi_v)\cos\theta_v \sin\theta_v d\theta_v d\phi_v L_i(\theta_i, \phi_i)\cos\theta_i \sin\theta_i d\theta_i d\phi_i}{\int_{2\pi} L_i(\theta_i, \phi_i)\cos\theta_i \sin\theta_i d\theta_i d\phi_i}$$

$$= \frac{\int_{2\pi} A_{\mathrm{DHR}}(\theta_i, \phi_i) L_i(\theta_i, \phi_i)\cos\theta_i \sin\theta_i d\theta_i d\phi_i}{\int_{2\pi} L_i(\theta_i, \phi_i)\cos\theta_i \sin\theta_i d\theta_i d\phi_i} \quad (7)$$

where use was made of Eqs. (1) and (6). Since A_{BHR} generally depends on the incident illumination L_i, this albedo is not just a function of the intrinsic scattering properties of the surface as described by the BRDF f_r. However, for the special case when L_i is isotropic, then

$$A_{BHR} = A_{\mathrm{WSA}} = \frac{1}{\pi}\int_{2\pi} A_{\mathrm{DHR}}(\theta_i, \phi_i)\cos\theta_i \sin\theta_i d\theta_i d\phi_i \quad (8)$$

and A_{WSA} is only a function of the surface scattering properties. This case is also known as "the white sky albedo" (WSA). It is the albedo for isotropic diffuse light only, with no direct radiation (comparable but not equivalent to totally overcast sky conditions) — thus the "white sky" designation. The measurement of albedo in the field generally is the bihemispherical reflectance A_{BHR}. If the directional-hemispherical reflectance A_{DHR} or A_{WSA} is required, then the atmospheric effects, as expressed in Eq. (7), must be removed. That is, A_{BHR} must be atmospherically corrected.

2.3.4. Narrowband versus Broadband Albedo

The term albedo is used interchangeably with bihemispherical reflectance. However, albedo has traditionally been applied to broad spectral bands, as stated in section **2.3.1**. Where applied to narrow bands, it is most properly termed spectral or narrowband albedo. For specific applications, albedo integrated over a defined band may be desirable. For example, photosynthetically-active radiation (PAR) (0.4–0.7 μm) is of special interest to carbon balance modelers, who are concerned with the fixation of carbon by biospheric photosynthesis. For surface energy balance studies and the surface interaction modules of global and regional climate models, several broad bands are typically used: total shortwave radiation (0.25–5.0 μm) and shortwave broken into visible (<0.7 μm) and short infrared (>0.7 μm) spectral bands.

Extrapolation from narrowband to broadband albedos, although straightforward, requires modeling both the spectral distribution of surface incident and reflected flux in those portions of the broad spectral region where measurements are not available. For surface measurements, spectral downwelling radiance is a function of atmospheric conditions, so narrowband to broadband conversion requires some assumptions about (or measurements of) the atmospheric state. Spectral reflectances in unmeasured spectral regions are typically modeled by a spline fit to observed measurements. For normal surface targets and atmospheric conditions typical of good surface viewing, however, the conversion is not overly sensitive to these assumptions provided that the broadband spectral region is sampled at reasonable locations [Liang *et al.*, 1998].

3. Conclusions

In addition to using precise reflectance nomenclature, an investigator should also strive to describe in as much detail as possible the context of the measurements. This includes the sensor field-of-view, spectral characteristics, view and illumination geometries. Ancillary data may include atmospheric optical depth, aerosol type or composition, water vapor, ozone conditions, presence of cloud or cirrus, and the state of the soil and vegetation. A determination of surface reflectance properties from TOA radiances requires modeling to separate the effects of atmospheric absorption, scattering and emission on the TOA radiance from those of surface scattering. This separation process is not easy but can be done with reasonable accuracy given the appropriate ancillary data. Indeed, a major advance in the data processing of recent instruments like MODIS and MISR is the ability to produce on an operational basis"atmospherically corrected" surface products. Likewise, data acquired with surface instruments must also be processed to remove atmospheric effects if the inherent reflectance properties of the surface are required.

A better understanding of our Earth system will be facilitated by both the recent advances in technology and methodologies, coupled with the synergism of global scale, on-orbit data acquisitions and in-situ validations and local-scale observations. A preciseness in data analysis includes the utilization of a preciseness in reflectance nomenclature.

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